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TOPOLOGY, SIMULATION AND IMAGES OF BIOLOGICAL PORES RELATED TO DIFFUSION IN SOILS

André Kretzschmar and Pascal Monestiez*
INRA, 17 rue Sully 21034 DIJON - France
*INRA, Biométrie, Domaine St Paul, 84140 MONTFAVET - France

ABSTRACT

Diffusion processes in soil may be regarded through the classical equations, where gas flows are governed by the concentration gradiant and the distance over which the diffusion occurs..

But it can be assumed that, when the biological pores are large enough to be considered similar to the surface, the actual distance, from the surface to one given level into the soil, which governs the gas flow rate is that of the minimum pathway utilizing the most efficient suite of large pores; the lenght of this pathway is obtained by summing up the respective distances between all the pores belonging to a given suite.

The structure of the studied biological pores is a "non connected network". By the first step of simulation, different 3D structures are obtained, over which the minimum pathway is calculated through the simulation of diffusion process : at each time of diffusion progression from the surface, images of the volume concerned by diffusion are obtained.

The length of the minimum pathway, depending on the network density and on the mean length of the pores is shown to be 4 to 10 times shorter than the observed distance. The density effect is mean length-dependant; an example of 3D diagram is given to show gas diffusion heterogeneity and gas expanding to the whole soil volume.

Keywords : biological pores, gas diffusion, non connected network, 3D images, simulation.

INTRODUCTION

Soil fertility can be regarded as related to the ability of soil structures in diffusing gases, mainly oxygen; the efficiency of theses structures governs the maximal depth of biological activity. Diffusing structures may occur from physico-chemical processes (mechanical response of clays to water potential) or directly from the activities of living beings inhabiting soil (voids left by dead roots or burrows opened by animals). In the case of earthworm burrow systems, the seasonal variations of these pore structures (Kretzschmar, 1982) leads to an understanding of these variations as a behavioural response to the environmental conditions.

On the other hand, it seems to be relevant to focus the study of gas diffusion on spatial heterogeneity because the respiration processes are generally the minimal pathway is given by adding the distance between this deepest burrow and that one by which it has been reached, to all the distances between the burrows by which, successively, the deepest has been reached.

RESULTS AND DISCUSSION

1. Images of diffusion from burrow system (density : 450). Figures 1 and 2 show two steps in the diffusion process, respectively corresponding to a front diffusion depth of 20 and 160mm; the deepest level reached is respectively 340 and 966mm; the number of burrows involved by diffusion is respectively 111 and 407. The black parts of these images represent the section of diffusing burrows at the side of the simulated sample. In figure 1, the diffusing burrows which are connected to the surface, have a diffusing diameter equal to the front depth (i.e. 20mm). The smaller ones have been reached by the next steps of diffusion, directly by the surface or by another diffusing burrow. In figure 2, most of the burrow system are diffusing and the efficiency of the system can be considered as optimal at this level. When going down further, the diffusion of the deepest diffusing burrows have only little chance to encounter the remaining 43 (450-407=43) burrows; then diffusion is mainly a soil diffusing process where the burrow system plays only a little function. Comparison of both figures shows the decreasing of biological structure efficiency with depth.

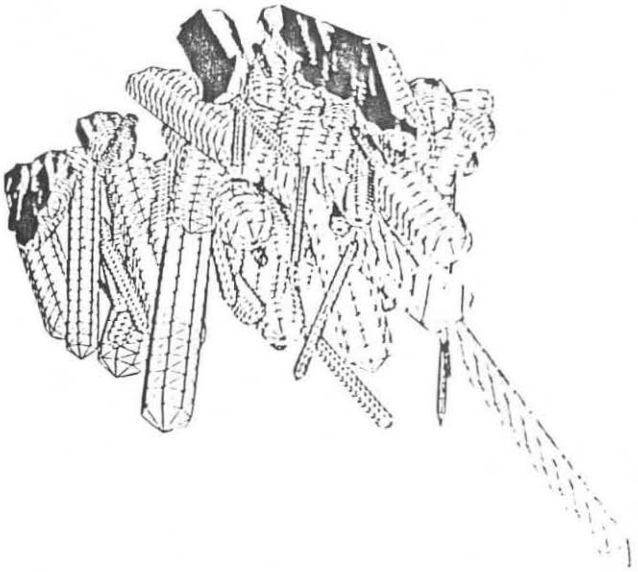

Figure 1. Image of the volume of diffusing system (front level = 20mm)

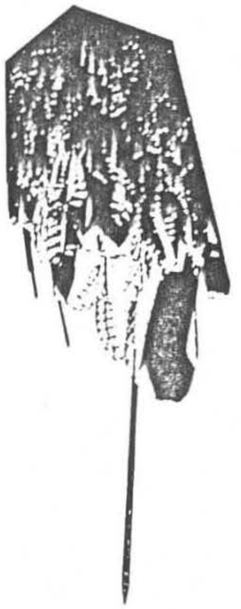

Figure 2. Image of the volume of diffusing system (front level = 160mm)

2. Structures : effect of burrow mean length and system density on the minimum pathway length. Figure 3 presents the length of the minimum pathway (DIST) versus the depth (DEPTH) of the sample bottom. The "stair" shaped curves correspond to the succession of burrow effect (horizontal part) and soil diffusion (1.0 coefficent straight line part). The effect of mean burrow

temporary and closely localized; consequently, oxygen availability at any place in the soil can be studied as a local process (instead of as a general one considering the soil as a whole).

In a previous study (Kretzschmar, in press), the structural parameter which has been shown to point out the function of earthworm burrow systems in diffusion processes, is what we call the "minimal pathway" and which is defined as follows : if diffusion into the burrow is regarded as similar to the diffusion on the surface, "soil" diffusion depends only on the distances between the burrows; then, from the surface to the bottom of the profile (here defined at 1000mm), there exists, over the non connected burrow system, one pathway for which the sum of the respective distances between the succesive burrows belonging to this pathway is minimal. This paper deals with the variations of this minimal pathway versus density and mean burrow length and gives an image of the soil diffusion simulated by this way.

METHODS

1. Simulated burrow systems. The full description of natural earthworm burrow systems have been performed *in situ* with the following method : a face, from a large pit (2x2x2m), was rendered as flat and vertical as possible. A column of soil (10x10x200cm) was described by destroying it little by little and every burrow was characterized by the three dimentionnal coordinates of its extremities and of the points where the burrow direction was changing, and by its diameter. These observations have been made six times : June, December, February, May, August and November (Kretzschmar, 1978, 1982). When observed in natural conditions, earthworm burrow systems have been shown as a non connected set of (coarsly) cylindrical shaped tubes; each of them can be defined by four main characteristics : length, angular orientation versus horizontal plane, position of central depth coordinates in the profile and diameter. For the results presented here, burrow systems are simulated by the following method: "tube-burrows" are defined with the four above mentioned characteristics; they are distributed in a virtual "soil sample" 30x30x1000mm in size. The density of the simulated burrow systems is governed by the number of burrow units distributed in this "sample". The distribution of the four characteristics (exponential for the three first and normal for diameter) have been fitted versus observed systems (op. cit.). For every system described here, mean value of angular orientation versus horizontal plane is 0.78 rd and of central depth coordinate is 300mm. The different burrow systems are obtained by changing mean burrow length (45mm, 55mm, 65mm) or burrow system density (450, 900, 1350; the two latter are obtained by adding 450 new burrow units to the previous systems in order to point out the effect of density only, without an heterogeneity effect observable with independent systems).

2. Minimal pathway : algorithm. Under the assumption above mentioned (the diffusion into the burrow is similar to that on the surface), the calculation algorithm for minimal pathway is as follows : diffusion process is simulated going down from the surface, as a horizontal front, progressing step by step (step=1mm). At each step, when a burrow is reached by the diffusion front, the whole surface of the burrow is considered as diffusing; then, the next diffusion step, the "diffusing" volume of a reached burrow is increasing, in term of diameter and length, by twice the step value. Burrows can be reached either directly by the surface or by the diffusion front or by the expansion, step by step, of a diffusing burrow. The first time the lowest coordinates of a diffusing burrow reaches the level given as the bottom of the system (here 1000mm), the value of

length can be observed in comparing the different curves on the same line (mean burrow length equal to 45, 55, 65mm for replicates 1, 2, 3). Replicate 1 shows a rather regular effect in the decreasing of DIST, while in replicate 2 it is possible to see the effect of a deep burrow in shortening DIST (55-2) in such a way that the increasing of mean burrow length from 55 to 65 has a very poor effect. The effect of a long middle burrow (55-3 compared to 45-3) brings only a little shortening of DIST because the quasi absence of burrow at the bottom of the sample, but when a long burrow appears with depth (65-3), DIST is greatly shortened.

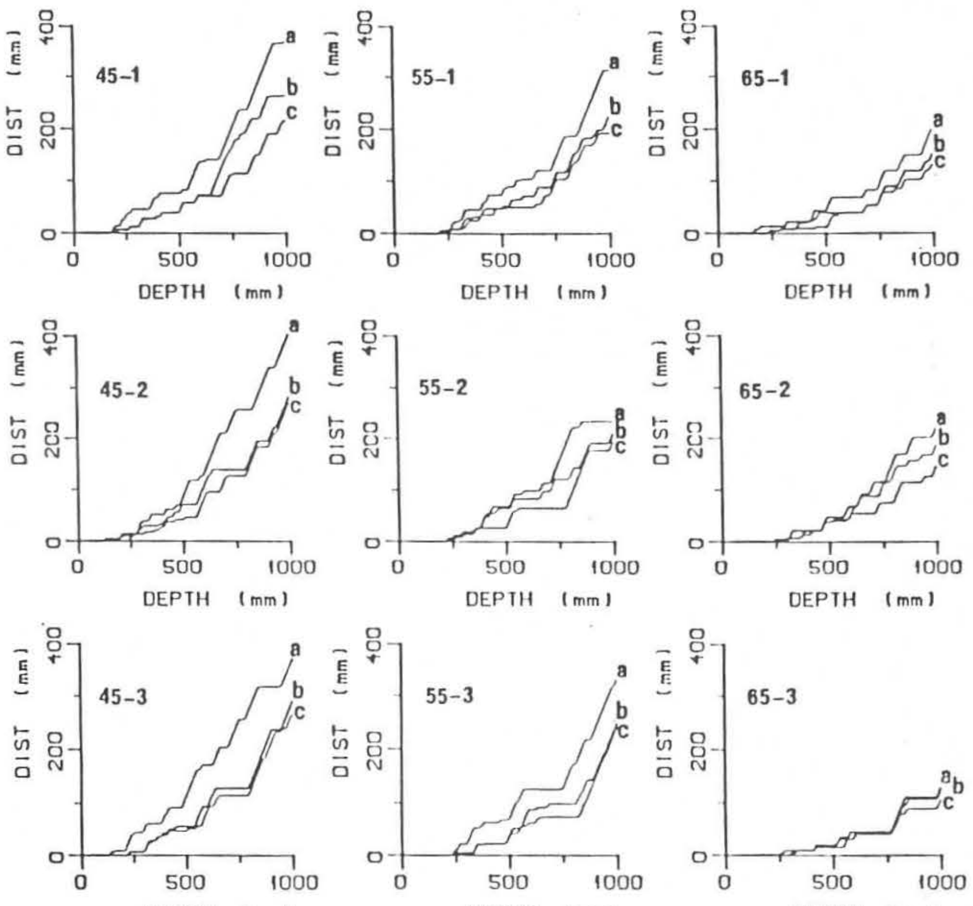

Figure 3. Evolution of minimum pathway length (DIST) with depth(DEPTH); curves are given for three replicates (1, 2, 3), three mean burrow lengths (45, 55, 65mm) and three system densities (a=450, b=900, c=1350 units).

The effect of system density is shown by comparing the three curves a, b and c of each part (45-1 to 65-3) of figure 3. As a rule, the difference between the curves a (=450) and b (=900) seems to be greater than the difference between b and c (=1350); that can suggest a threshold effect. The effect of density seems also to be less with the increasing of mean length especially when a long and efficient burrow occurs (65-3). The mean length dependance of density effect is probably due to the combined action of the actual mean length of the population of burrow with the influence of some long, but rare, burrows. This particularity points out the question of the structure of the burrow system regarding gas diffusion : the diffusion at a local scale can be regarded rather as mean length dependant, while the diffusion in the system as a whole would be under the influence of the occurence, with a low probability, of some long burrows.

3. Structural and functional heterogeneity. Because the specific effect of mean burrow length and of long burrows, the values of the minimum pathway length estimation over the different sytems show an important variation; table 1 gives these values : although replicate number is too small for statistical estimation, it seems that the variability could be regarded as a source of soil diffusion heterogeneity. One consequence of long burrow is the possibility of a non-diffusing soil zone at a given level, when the lower levels are diffusing; this is shown by the figure 4 : when the proportion of diffusing saturation for a given DIST, is not continuously decreasing with DEPTH, that means the effeciency of a long burrow in connecting by diffusion a local concentration of burrows at its bottom level is better than that one occuring at its top or at its middle level. This can be seen at DEPTH=800mm for DIST=150 to 250mm.

	45 mm		55 mm		65 mm	
450	1	368.7	1	312.4	1	198.9
	2	402.7	2	233.9	2	220.4
	3	371.5	3	330.9	3	129.8
900	1	264.4	1	224.1	1	152.1
	2	281.6	2	208.5	2	185.7
	3	290.4	3	247.2	3	125.0
1350	1	216.6	1	193.0	1	135.0
	2	269.6	2	194.7	2	144.6
	3	264.0	3	240.5	3	106.9

Table 1. Minimum pathway length (mm) for the different simulated systems (density : 450, 900, 1350 units; burrow mean length : 45, 55, 65mm; replicates : 1, 2, 3) when system bottom is 1000mm deep.

CONCLUSIONS

The results and comments above mentioned do not deal with gas diffusion in soil as it is usual to do; moreover, we do not regard these results as an estimation (or a way to reach it) of a soil diffusion coefficient. Despite the fact that the minimum pathway length should have a relevant significance in the diffusion processes (as an estimate of δz in Fick's equations), we focus this study on the spatial structures of the burrow systems and the functional importance of heterogeneity. The relationship between density effect and mean burrow length effect on one hand and the role of long burrows on heterogeniety features (non diffusing isolated place, variability of minimum pathway length) on the other can be regarded as the main results; the utilization of 3D images, especially in describing the evolution of the diffusion process step by step, is devoted to point out the structures involved either in local or in global properties of the burrow systems.

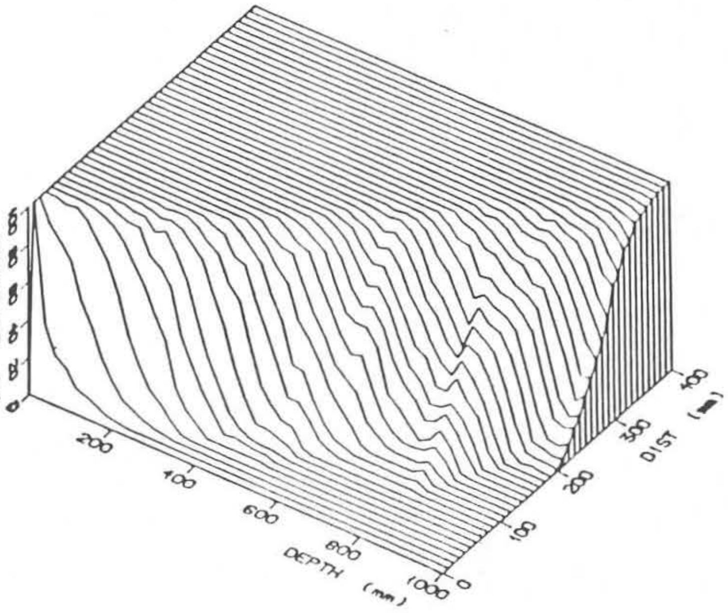

Figure 4. Variations of the proportion of soil diffusing saturation (% PERCENT SAT.), following DEPTH(mm), at each value of DIST(mm)

However, improvements can be brought to this method : bias due to the section of burrows going out of the defined sample is not yet estimated; the algorithm for minimum pathway estimation could perhaps be improved by applying more sophisticated methods which mainly allows us to save time in computation and to perform at statisticaly consistent numbers of replicates.

ACKNOWLEDGEMENTS
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